An Experimental Study on the Vibrations and Grid-to-Rod Fretting Wear in PWR Fuel

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Abstract

An experimental study on the vibrations and grid-to-rod fretting wear is performed based on extensive fretting wear tests of the PWR fuel. The fretting wear between grid and fuel rod is initiated at a certain critical gap correlated with a critical work rate. A critical gap between grid and rod is formed due to in-reactor performance of fuel, thermal relaxation of grid spring and irradiation growth of grid strap, etc. A critical work rate is generated with the combination of high frequency vibration of grid strap, fuel rod vibration and fuel assembly vibration. Fuel assembly fretting wear has been evaluated using the grid-to-rod fretting wear rates as a function of initial gap size under a certain work rate determined by the fuel assembly design and a test flow rate considered. Based on the fretting wear tests, a methodology is proposed for predicting fretting wear rate as a function of grid-to-rod gap size that is strongly dependent on the fuel assembly design as well as the grid-to-rod contact geometry.

1. Introduction

A PLUS7 fuel assembly, which is an advanced fuel for Korean Standard Nuclear Power Plants (KSNP), has been developed to get the thermal margin increase, failure free and high seismic resistance, etc. comparing to the current fuel. The fuel assembly consists of 236 fuel rods, 4 guide thimbles and an instrumentation tube, 11 grids which include 2 Inconel top/bottom grids and 9 Zirlo mid grids to support fuel rods, a debris protective grid and easy reconstitutable top/bottom nozzles (Fig. 1). The guide thimbles/instrumentation tube, grids and top/bottom nozzles form the skeleton of the fuel assembly. The grids are fabricated from Zirlo or Inconel straps interlocked in an egg crate fashion and welded together. The grids maintain the rod pitch over the fuel rods by providing positive lateral restraint. The fuel rods

are restrained from axial motion by the frictional forces developed by the grid springs. Each cell of the grid contains two springs and four dimples. Each spring presses the fuel rod against two dimples, and thereby restricting relative motion between the grids and the fuel rods. The grids are fastened to the guide thimbles/instrumentation tube by welding or using mechanical fittings. The fuel rods consist of UO_2 pellets, a plenum spring, all encapsulated within a Zirlo cladding tube which is welded into a hermetic enclosure.

A grid-to-rod fretting wear in the Pressurized Water Reactor (PWR) fuel assembly is studied through the extensive fretting wear tests during advanced fuel development programs. Vibration-induced fretting wear is initiated at a certain critical gap correlated with a critical work rate. A critical gap between grid and rod forms due to in-reactor performance of fuel, thermal relaxation of grid spring and irradiation growth of grid strap, etc. A critical work rate is generated with the combination of high frequency vibration of grid strap, fuel rod vibration and fuel assembly vibration. Fuel assembly vibration tests have been performed to check if vibration amplitudes are big enough to induce fretting wear as well as if a self-excited resonance occurs in the fuel assembly. In addition, fuel assembly fretting wear tests also have been performed to evaluate the grid-to-rod fretting wear rates as a function of initial gap size under a certain work rate determined by the fuel assembly design and a test flow rate considered. Single grid-to-rod fretting wear tests have been performed to derive empirical wear coefficients under a constant work rate, which may be used to evaluate fuel failure time due to the fretting wear. These single fretting wear test results show that grid-to-rod gap size variation during the test depends on the grid-to-rod contact shape. Based on the aforementioned fretting wear tests, this paper proposes a methodology for predicting fretting wear rate as a function of grid-to-rod gap size that is strongly dependent on the fuel assembly design as well as the grid-to-rod contact geometry.

2. Fretting Wear Behavior in Reactor

The fuel rods are supported by several spacer grids because they have big slenderness ratios. The fuel assembly and the fuel rods are subjected to flow induced vibration and result in fretting wear at the grid support positions.

At the Vingsbo and Soderberg's fretting map [1], four wear regimes were suggested based on the amplitude of relative motion between the contact bodies. In stick regime of small relative motion, the bodies experience little damage due to wear and no fatigue crack growth. In mixed stick and slip regime, wear and corrosion effects are small but accelerated crack growth can lead to reduced life. Fretting wear occurs in the gross slip regime. There are unidirectional sliding wear damages at larger amplitude of motion. It is, therefore, expected that the fretting wear in nuclear fuel rod be initiated when a grid-to-rod gap reaches a critical value. As per Ref. 2, fretting wear damage related to dynamic interaction between a vibrating fuel rod and its supporting grid is formulated in terms of the work-rate parameter which is simply the integral of the contact force times the sliding distance per unit time. The vibration energy is related to the amplitude, frequency, mode shape, mass and damping. Because there are several types of contacts between grid and rod due to uncertainties on straightness [3], alignment and contact forces, it is not easy to formulate the vibration and the resulting fretting wear quantitatively.

Initially, the mid grid springs/dimples are fabricated with a compression of 10 to 25 mils against fuel rods. During irradiation in reactor, the fuel rod cladding creeps down, the mid grid springs and dimples relax, and mid grid straps grow to rolling direction, resulting in a gap between the fuel rods and the grids. Fuel rod creeps down due to the pressure difference between a constant system pressure of 2,250 psi and rod internal pressure increasing with time. The fuel rod diameter decreases until the inner diameter of the cladding contacts the outer diameter of the fuel pellets. At the same time, the grid spring forces relax due to irradiation and stress until the grid spring preloads disappear. In addition, the grid straps grow due to irradiation and corrosion. A grid-to-rod gap occurs after a certain time in reactor in the end.

3. Vibration Tests

The cross flow in PWR nuclear fuel can occur by unstable flow distribution in inlet, outlet and baffle regions of reactor, by pressure difference between fuel assemblies in mixed core, and by flow mixing vanes installed for thermal margin increase. In addition, the effect of this cross flow on fuel behavior is superposed to that of axial flow in reactor. The effect of the flow on fuel vibration and wear is mainly caused by turbulent flow because the coolant flow velocity in reactor is low enough not to cause the fuel rod to fluid elastic instability [4].

The sources to induce fuel rod failure can be caused by relative motion between fuel rod and its supporting grid at the grid positions. The sources to cause the relative motion due to coolant flow are grid strap vibration, fuel rod vibration, and fuel assembly vibration, etc. Grid strap vibration is caused by vorticities shedding at high frequency range.

Fuel rod of about 0.374 inch in diameter and 160 inch in length has such a big slenderness ratio and vibrates due to fast coolant flow in reactor. Several grids, therefore, support this rod adequately so that its natural frequencies are inconsistent with the external excitation frequencies. Fuel assembly of about 8 inch by 8 inch square and 15 ft in length also vibrates due to fast coolant flow.

Fuel rod and assembly vibrations can be measured by installing accelerometers at mid spans between supporting grids, and at supporting grid positions or by installing the measuring devices on flow housing at grid positions.

3.1. Grid Strap Vibration

High frequency grid strap vibration test has been performed to check if there is a potential enough to induce the relative motion between fuel rod and grid [5]. Even though the effect of strap vibration on the motion is small, this test is performed to find out the strap vibration amplitude at the reactor operating range. Vibration amplitudes at several positions of grid strap were measured by increasing the flow rate after loading a 5x5 bundle into hydraulic test housing.

Fig. 2 shows the comparison of relative peak to peak amplitudes vs. the test flow rate. A fuel bundle with a convex shaped grid (grid type A) has higher amplitude at the reactor operating range while a bundle of concave shaped grid (grid type B) does not have any peaks and has a tenth of amplitude of grid type A at the reactor operating range.

3.2. Fuel Assembly Vibration Using As-Built Grids

Fuel assembly vibration tests have been performed using full-scale test fuel assembly [6]. A test bundle is the same as the commercial nuclear fuels except using the depleted UO_2 pellets.

With loading a test fuel assembly into the hydraulic test loop that has displacement transducers on the housing at grid positions, assembly vibration tests have been performed. The orbit motion plots have been obtained from the displacement transducer measurements. A typical plot in Fig. 3 shows that the measured mid grid did not have any contacts with the flow housing.

The flow sweep tests have been performed by increasing the flow rate until the maximum achievable flow rate at 380 degrees in Fahrenheit. A waterfall plot for a typical displacement transducer is shown in Fig. 4. This figure shows that the fuel assembly vibration is stable with only the first few modes slightly excited by the turbulent axial flow under the reactor operating range. It means that there is no indication of abnormal flow induced vibration response throughout the flow range.

After the sweep test, the flow dwell tests have been performed increasing the flow increment of 50 GPM. Fig. 5 shows the comparison of relative amplitudes as a function of the test flow rate. A slightly excited motion under the operating range in this figure is consistent with that shown in Fig. 4. A fuel bundle of grid type A has higher amplitude while that of grid type B does not have any peaks within the reactor operating range again.

3.3. Fuel Assembly and Rod Vibration Using Cell Sized Grids

Fuel assembly and rod vibration tests have been performed with loading two bundles side by side into hydraulic test loop [7]. A test bundle of grid type B has about 10% higher pressure drop than the other test bundle of grid type C. Therefore, cross flow can occur between two bundles. Grid type B has three kinds of cell sizes which are as-built, 4 mil gap and 10 mil gap between grid and rod while grid type C has been used as a conditioning bundle to evaluate the effect of cross flow. All mid grids of grid type B have been slightly oxidized. In addition, oxidized and non-oxidized fuel rods have been loaded for a bundle of grid type B. Fig. 6 shows the comparison results of relative amplitudes at a specific span and grid positions typically. Even though there are some scatters at some flow rate due to rod behavior after grid-to-rod contact, it has a trend that the vibration amplitude increases with the flow rate. Vibration of fuel rod with grid-to-rod gap of 4 mils as shown in Fig. 7 is similar to that of fuel assembly measured at as-built cell condition. The rod natural frequencies at the gapped cell conditions are lower than those at as-built cell condition as shown in Fig. A1 of Appendix A.

4. Fretting Wear Tests and Evaluation

After the aforementioned two assemblies have been tested in the hydraulic loop during 500 hr, all measurable wear scars have been measured and evaluated. All slightly oxidized rods within any gapped cells as well as all non-oxidized rods within as-built cells did not

have any measurable wear marks. In this paper, non-oxidized rods with grid-to-rod gaps of 4 mils and 10 mils are evaluated. The wear scars are much scattered at each grid position and at each cell location. Fig. 8 shows the relative wear scar depths at each grid cell in a typical grid position. Initial wear is very sensitive to bundle straightness and grid-to-rod contact conditions, etc. It requires more intensive evaluation to formulate the scatters mathematically because there are uncertainties in statistical parameters and complicated cross flow, etc. The wear depth rate vs. initial gap size is shown in Fig. 9 based on the maximum wear depth at each initial gap size. The wear depth rate of fuel rods having 4 mils is smaller than that of 10 mil gaps. As per reference 8, no measurable wear was observed in any cells with interference between grid and rod. Assuming the wear depth rate increases by initial grid-to-rod gap size, an wear depth rate for grid type B could be acquired as a function of initial gap size below:

$$WDR = 0.0005 \text{ x (GS) } - 0.001 \tag{1}$$

Where WDR is wear depth rate in mils/hr
GS is grid-to-rod gap in mils (GS>2 mils)

By using the above expression, the fuel failure time may be calculated about 200 days assuming fretting wear is initiated at the grid-to-rod gap of 4 mils. To evaluate if this type of fuel keeps the integrity on fretting wear point of view, it needs to evaluate the time to reach the critical gap and the critical work rate. Another better correlation can be expected by adopting the design modification with springs and dimples of edge radius rather than edge chamfer, particularly in case of the conformal contact between grid and rod.

Based on single grid-to-rod fretting wear test results, it is found that the final gap sizes at given initial grid-to-rod gap sizes and the same work rates are dependent on grid types. The gap size of grid type A after the test has been 20 to 30% bigger than that of grid type B. Considering that bigger gap sizes resulted in bigger wear rate at assembly-wise fretting wear test, grid type A will have shorter failure time than grid type B.

5. Conclusions

The followings have been obtained through the evaluation of the extensive out-of-pile tests performed during advanced fuel development program.

(1) The amount of fretting wear in PWR nuclear fuel depends on the extent of grid strap vibration, fuel rod vibration and fuel assembly vibration. Any resonance caused by these vibration mechanisms should be eliminated and the vibration amplitudes should be kept as low as possible at reactor operating range.

(2) Vibration-induced fretting wear is initiated at a certain critical gap correlated with a critical work rate.

(3) A methodology in which wear depth rate depends on grid-to-rod gap size, is proposed to evaluate fretting wear in the PWR nuclear fuel based on the extensive fretting wear tests.

(4) Based on the proposed methodology, a conformal spring is superior to typical convex shaped springs with regard to fretting wear resistance since the former generates relatively bigger contact area than the latter.

Appendix A. PLUS7 Fuel Rod Modal Analysis Using Computer Code

PLUS7 fuel rod natural frequencies and the first ten mode shapes have been obtained through the modal analysis by ANSYS/6.1 computer code [9]. Fuel rod and grids are modeled in air at room temperature condition using a lumped method. Gap and no gap conditions are simulated. Fig. A1 shows the natural frequencies by the mode shapes at different number of grid-to-rod gaps typically. The figure shows that the more gaps have the lower natural frequencies. In addition, it is expected that the natural frequencies will be reduced because of the effects of higher damping, added mass and loosely supported conditions in reactor.

Acknowledgements

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Easy Reconstitutable Top
Nozzle

Inconel Top Grid

Zirlo Mid Grids

Inconel Bottom Grid

Debris Protective Grid

Easy Reconstitutable Debris Filter
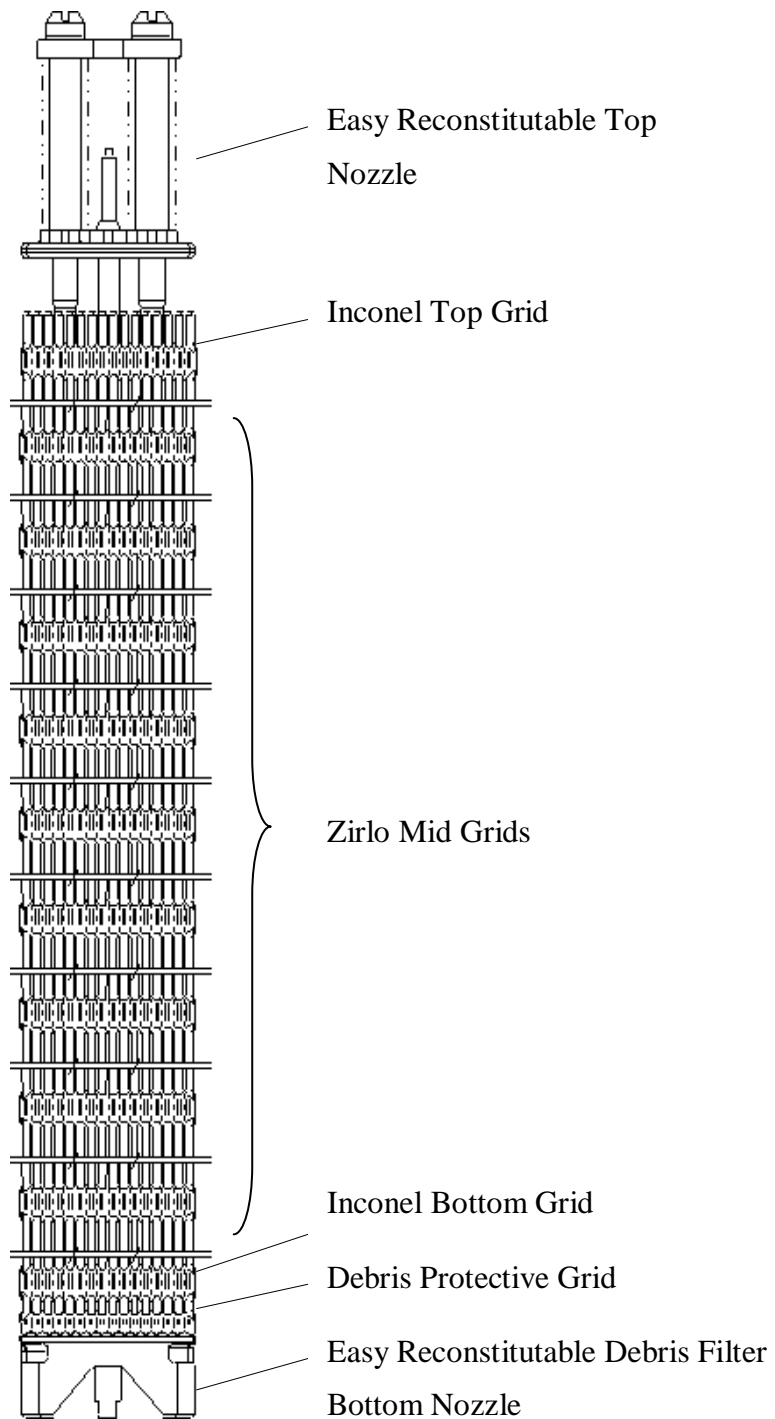Bottom Nozzle

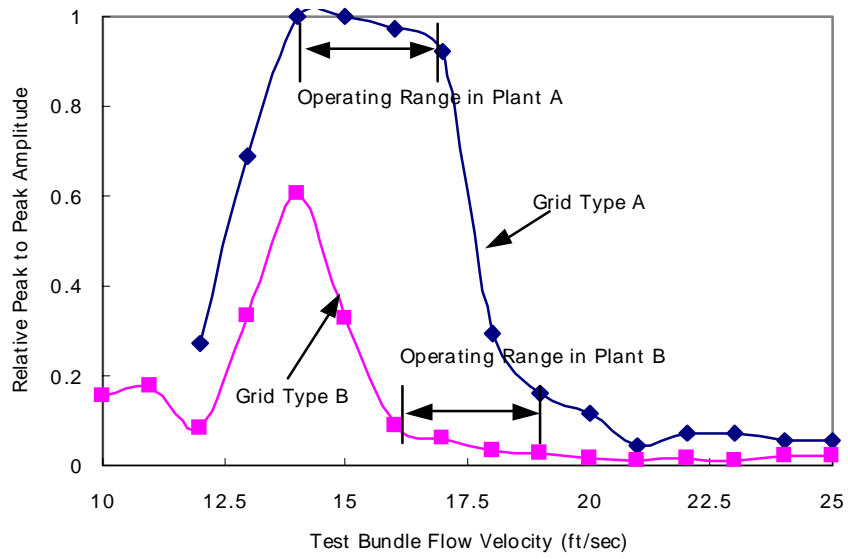Fig. 1 PLUS7 Fuel Assembly for Korean Standard Nuclear Power Plants

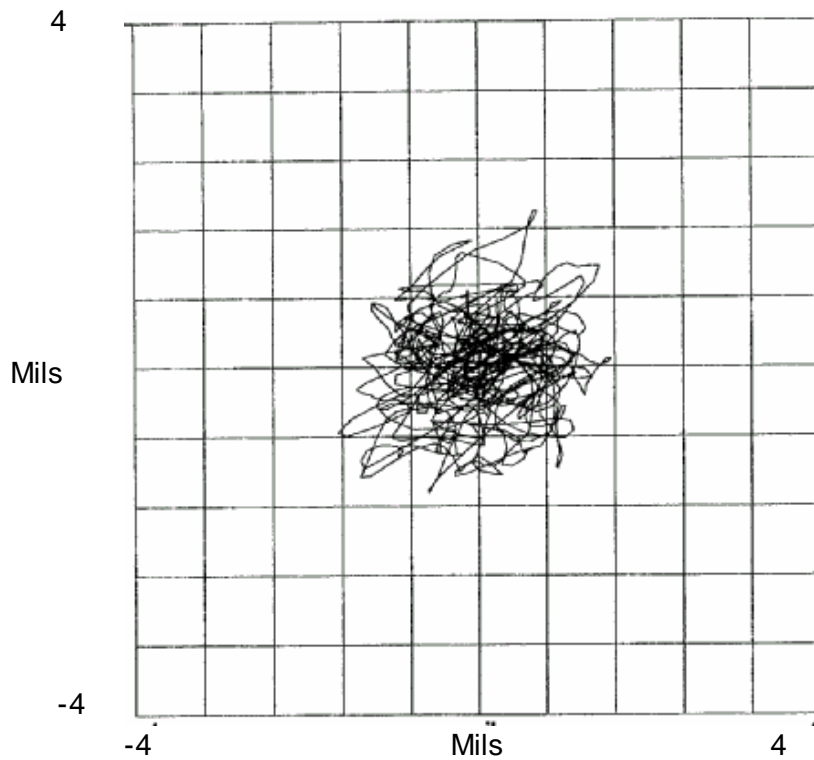Fig. 2. Flow-Induced Vibration Amplitudes of Two Different Types of Grid Straps

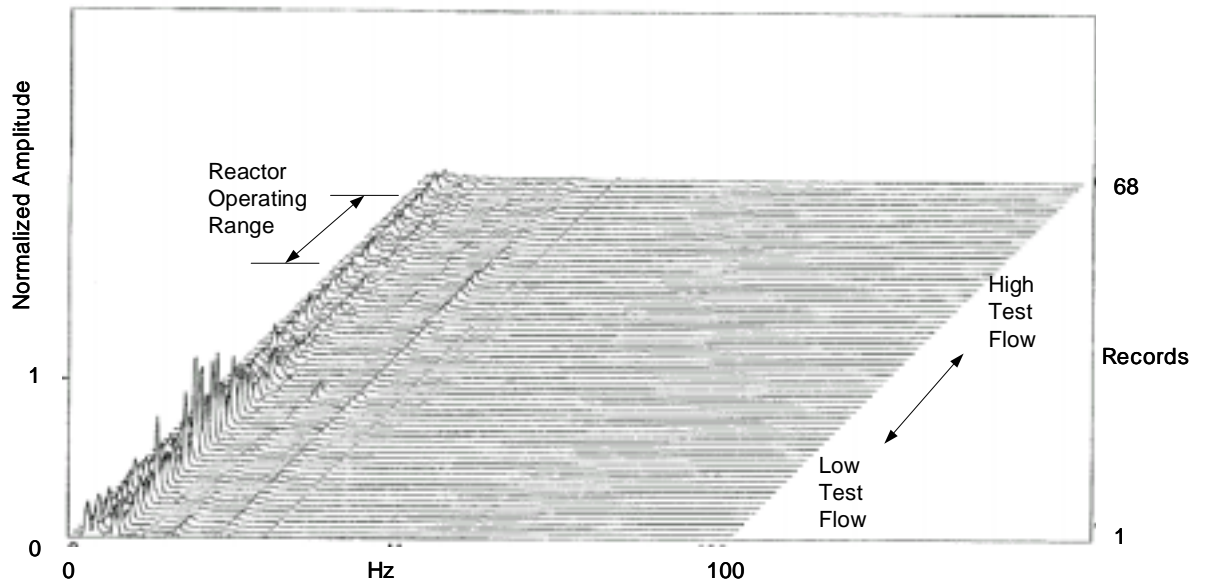Fig. 3. Typical PLUS7 Fuel Assembly Motion at 8th Mid Grid from Bottom

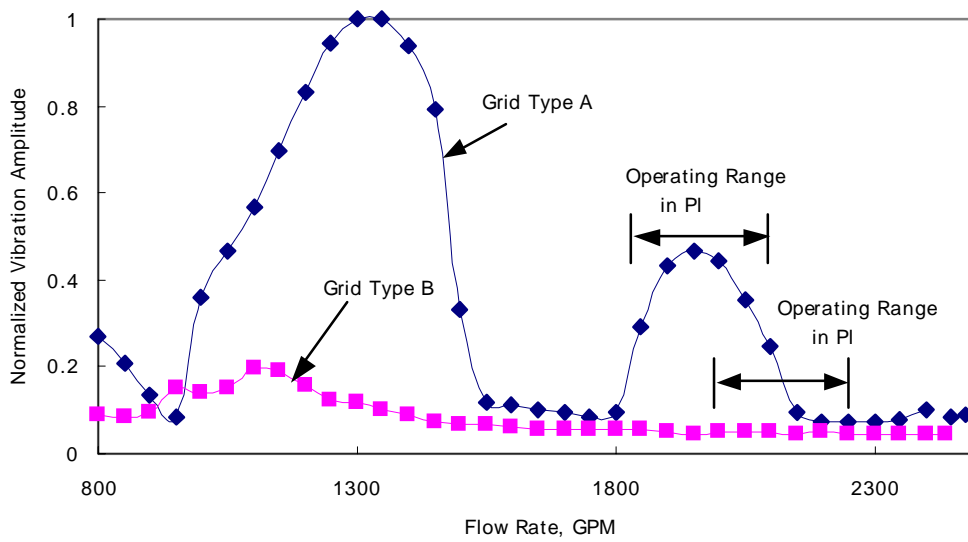Fig. 4. Typical Normalized PLUS7 Vibration Amplitude as a Function of Frequency by Increasing Flow Rate

Fig. 5. Comparison of Fuel Assembly Vibration between Grid Type A and B
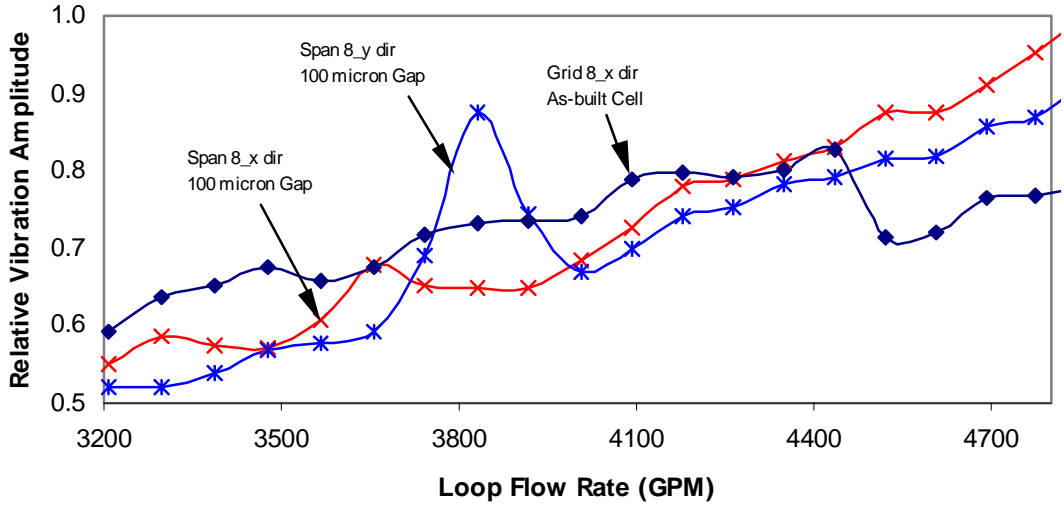
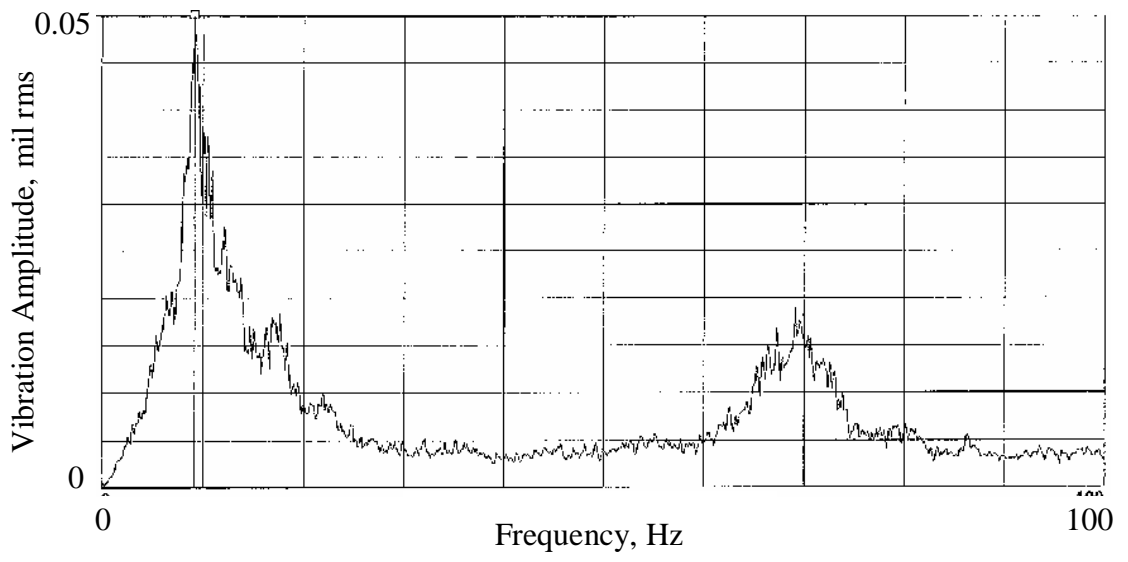Fig. 6. Assembly and Rod Vibration of Grid Type B (Typical)

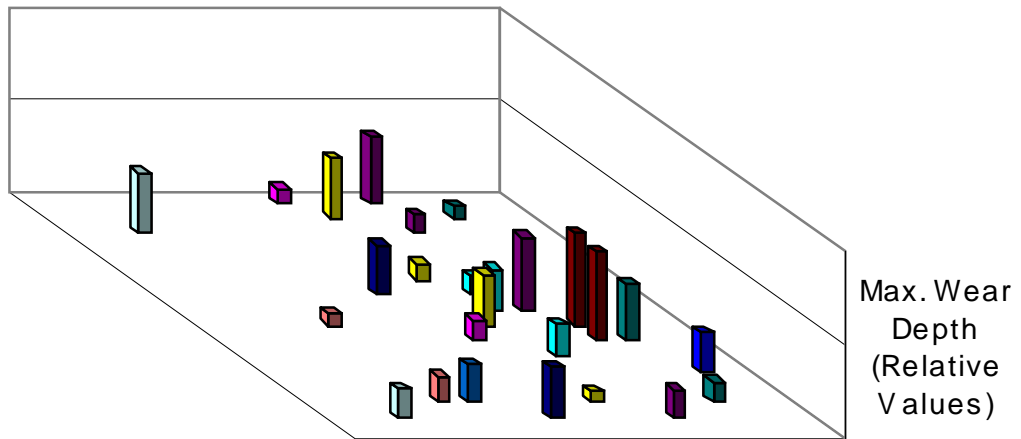Fig. 7. Fuel Rod Vibration of Grid Type B at Span 9 (Typical)

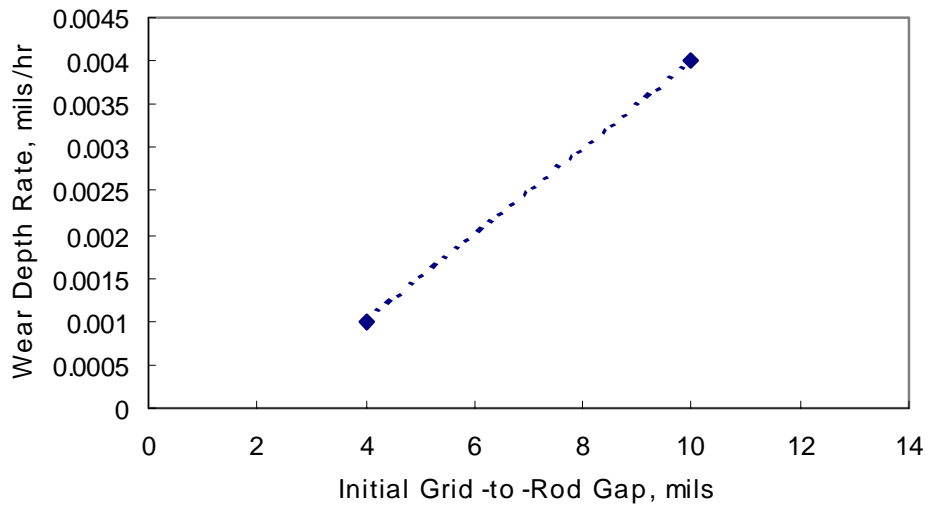Fig. 8. Relative Wear Depth at Each Cell at Typical Grid Position

Fig. 9. Wear Depth Rate against the Different Grid-to-Rod Gap Size
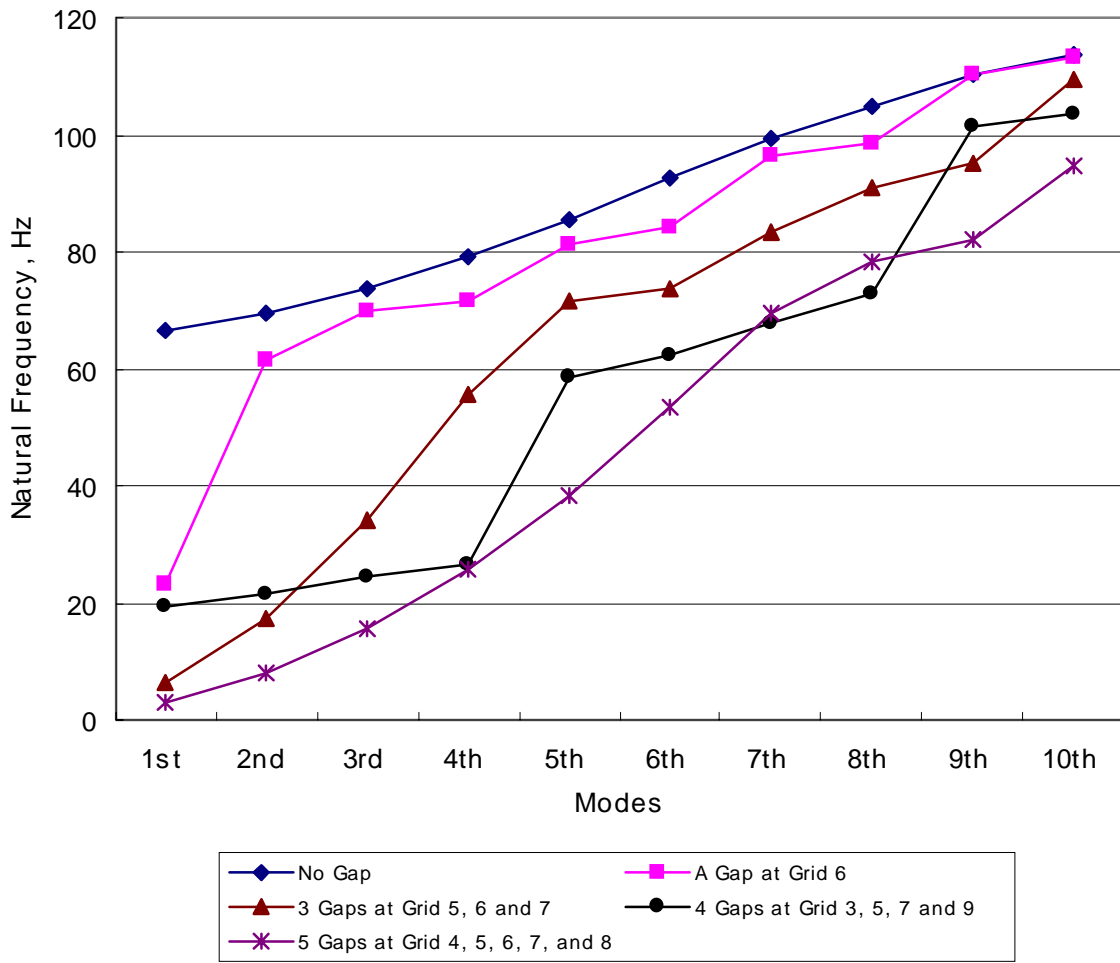
Based on the Maximum Wear Depth

Fig. A1. PLUS7 Fuel Rod Natural Frequencies by Modes at Several Gap Conditions